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A dynamic model of bank behaviour under multiple regulatory constraints

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Abstract

We develop a dynamic structural model of bank behaviour that provides a microeconomic foundation for bank capital and liquidity structures and analyses the e ects of changes in regulatory capital and liquidity requirements as well as their interaction. Our ndings suggest that adjustments in both types of requirements can have an impact on loan supply, with considerable heterogeneity across banks and over time. The model illustrates that banks' reactions depend on initial balance sheet conditions and reconciles evidence on short-term reductions in loan supply with ndings suggesting that better capitalized banks are better able to lend in the medium- to long-term.

Keywords: bank regulation, capital structure, liquidity structure, structural model
JEL classi cation: G21, G28, G32

Non-technical summary

Following the global financial crisis of 2007-08, policy makers around the world have launched a comprehensive reform programme aimed at increasing the banking sector's resilience against shocks. A key feature of this post-crisis regulatory framework is its multi-faceted nature, with banks being subjected to multiple regulatory constraints aimed at capturing the various risk dimensions on the solvency and liquidity side. Considering the variety of regulatory changes and the relative novelty of many reform elements, assessing the joint impact of the adapted framework on banks and the real economy is a challenging task for both regulators and academics.

In this paper, we develop a dynamic partial equilibrium model of bank behavior that aims at addressing these challenges by providing a microeconomic foundation for banks' capital and liquidity structures as well as their adjustments in response to regulatory changes and economic shocks. The model takes a private perspective, which is justified by the observation that banks' private adjustment decisions often transmit to the real economy via their impact on aggregate loan supply. Moreover, the model features regulatory constraints on risk-weighted capital ratios and liquidity ratios and is well suited for studying the interaction between these different types of requirements.

The stylized bank balance sheet in the model comprises loans and liquid assets on the asset side, and deposits, long- and short-term debt and equity on the liability side. Banks face uncertainty with respect to assets returns, funding costs, and deposit volumes, and need to consider various trade-offs simultaneously when taking decisions on how to adjust their balance sheet structure. Generally, taking more risk allows them to generate higher expected returns, while at the same time increasing the risk of breaching regulatory capital and/or liquidity requirements or having to raise fresh equity in the market. The model accommodates potential heterogeneity in banks' response functions, reflecting the possibility that reactions may depend on initial balance sheet conditions. This is important since different modes of adjustment may have different social implications, for example with respect to the evolution of aggregate loan supply and overall economic outcomes.

We estimate the model on data for 116 institutions supervised by the European Single Supervisory Mechanism (SSM), covering the quarters from 2014-Q1 to 2016-Q3 and containing very granular balance sheet and income statement information. We estimate the structural parameters of the model to match key balance sheet characteristics and dynamics observed in the supervisory data. The estimated structural parameters provide an explanation for voluntary capital and liquidity buffers based on precautionary motives and confirm that regulatory requirements are important determinants of actual capital and liquidity structures.

The model suggests that changes in capital and liquidity requirements can have a material

impact on banks' asset and liability structures and, consequently, aggregate lending in the economy. In particular, the model predicts that most banks fully replenish their voluntary bu ers in response to increases in capital requirements, with considerable heterogeneity in the mode of adjustment. This has important implications for the supply of loans. Generally, banks that are initially more constrained (i.e., closer to the minimum capital requirement) choose socially less desirable adjustment strategies, reducing loans considerably more than banks that are initially less constrained. Moreover, our model suggests considerable di erences between transitory and medium- to long-term e ects of higher capital requirements. While banks tend to reduce loans in the short run, they also accumulate additional capital by retaining earnings, which allows them to support lending at higher levels than before in the medium to long-run.

We further show that also changes in liquidity requirements can have sizable real e ects, depending in particular on their interaction with capital requirements. Following an increase in liquidity requirements banks react by holding a larger amount of liquid assets. Ceteris paribus, increasing the amount of assets decreases capital ratios, so that further adjustments in the supply of loans are necessary if banks wish to maintain constant voluntary capital bu ers.

This paper adds to the literature by proposing a novel methodology to study the dynamic adjustment of bank capital and liquidity structures. Moreover, it contributes to the literature by illustrating the trade-o s that banks need to consider in an environment with both capital and liquidity requirements in a dynamic setting, and by o ering insights on how capital and liquidity requirements may interact to determine the response of banks to changes in either capital or liquidity requirements.

Our results reconcile empirical evidence on negative short-run e ects of higher capital requirements and positive long-run e ects of higher bank capitalization. Moreover, they complement empirical evidence from the recent nancial crisis showing that retaining earnings is the preferred mode of adjusting to higher capital requirements. Overall, the results of the paper highlight that the impact of changes in capital requirements, and in particular the short-term lending reaction (which is often used as a proxy for the potential cost of policy measures), is likely to depend on how binding the constraints are prior to the policy change.

1 Introduction

Following the global financial crisis of 2007-08, policy makers around the world have launched a comprehensive reform programme aimed at increasing the banking sector's resilience against shocks. A key feature of this post-crisis regulatory framework is its multi-faceted nature, with banks being subjected to multiple regulatory constraints aimed at capturing the various risk dimensions on the solvency and liquidity side. Considering the variety of regulatory changes and the relative novelty of many reform elements, assessing the joint impact of the adapted framework on banks and the real economy is a challenging task for both regulators and academics (see, e.g., Financial Stability Board 2017). Existing models and empirical studies on regulatory impact assessment often focus on the effects of higher capital requirements on lending, while there is little evidence on the effects of liquidity regulation and the interaction of the various rules.[1] Moreover, empirical evidence on banks' reactions is often limited to reduced form estimates that make it difficult to foresee future adjustments (e.g., Aiyar et al. 2014, Behn et al. 2016b, Jimenez et al. 2017), and the theoretical banking literature has mainly been interested in normative, general equilibrium considerations with respect to the optimal level of regulation (e.g., Diamond and Rajan 2000, 2001, Admati and Hellwig 2013, DeAngelo and Stulz 2015).

In this paper, we develop a dynamic partial equilibrium model of bank behavior that aims at addressing these challenges by providing a microeconomic foundation for banks' capital and liquidity structures as well as their adjustments in response to regulatory changes and economic shocks. The model takes a private perspective, which is justified by the observation that banks' private adjustment decisions often transmit to the real economy via their impact on aggregate loan supply. Moreover, the model features regulatory constraints on risk-weighted capital ratios and liquidity ratios and is well suited for studying the interaction between these different types of requirements.

The stylized bank balance sheet in the model comprises loans and liquid assets on the asset side, and deposits, long- and short-term debt and equity on the liability side. Banks face uncertainty with respect to assets returns, funding costs, and deposit volumes, and need to consider various trade-offs simultaneously when taking decisions on how to adjust their balance sheet structure. Generally, taking more risk allows them to generate higher expected returns, while at the same time increasing the risk of breaching regulatory capital and/or liquidity requirements or having to raise fresh equity in the market. To insure against profitability shocks on the asset and/or funding side that can push capital ratios down, banks may hold additional

[1] See, for instance, Berger et al. (2008), Flannery and Rangan (2008), Mehran and Thakor (2011), or Allen et al. (2015). An early survey on the effects of capital requirements is provided by Thakor (1996). More recently, some papers started to investigate how multiple constraints interact with each other (e.g., Cecchetti and Kashyap 2016, Chami et al. 2017, Goel et al. 2017, Mankart et al. 2018).

voluntary bu ers on top of minimum capital requirements.[2] A similar precautionary motive for voluntary bu ers arises on the liquidity side, where banks need to have a su cient amount of liquid assets to insure against possible out ows of deposits or uctuations in liquid asset prices or the cost of short-term debt. Our model provides an economic rationale for the magnitude of these voluntary capital and liquidity bu ers and thus provides insights on the importance of precautionary motives in determining banks' actual capital and liquidity structures.[3] Moreover, the rich characterisation of economic uncertainty, banks' balance sheet structure and choices embedded in the model allows analysing how capital and liquidity structures evolve over time, how regulatory requirements interact with each other in shaping these dimensions, and how banks adapt them in response to changes in capital or liquidity requirements. With respect to the latter, the model accommodates potential heterogeneity in banks' response functions, re ecting the possibility that reactions may depend on initial balance sheet conditions. This is important since di erent modes of adjustment may have di erent social implications, for example with respect to the evolution of aggregate loan supply and overall economic outcomes.

We estimate the model on data for 116 institutions supervised by the European Single Supervisory Mechanism (SSM), covering the quarters from 2014-Q1 to 2016-Q3 and containing very granular balance sheet and income statement information. Using a Simulated Method of Moments approach, the model's structural parameters are obtained by matching key balance sheet characteristics and dynamics observed in the actual supervisory data. The estimated structural parameters provide an explanation for voluntary capital and liquidity bu ers based on precautionary motives (see, e.g., Brunnermeier and Sannikov 2014 and Valencia 2014) and con rm that regulatory requirements are important determinants of actual capital and liquidity structures. Moreover, the estimates are consistent with frictions that prevent banks from freely adjusting the amount of equity raised from external stakeholders. In line with the data, the model suggests that asset expansion is mainly nanced by debt issuance, while equity tends to be relatively sticky, so that leverage is a major determinant of overall balance sheet size (see, e.g., Adrian and Shin 2011). More speci cally, increases in liquid assets tend to be nanced with short-term debt, while long-term debt and equity are more attractive when it comes to nancing loans. Moreover, asset expansions are associated with a decrease in average asset risk,

[2] This precautionary motive for voluntary capital bu ers is reminiscent of the models by Brunnermeier and Sannikov (2014) and Valencia (2014). Valencia (2016) provides empirical evidence supporting such a motive.

[3] A common view in the literature on bank capital structure is that holding capital imposes some kind of cost on banks who consequently operate with capital ratios close to the regulatory minimum (e.g., Mishkin 2004, Van den Heuvel 2008, Mehran and Thakor 2011, Allen et al. 2015, DeAngelo and Stulz 2015). In such a situation, even small changes in requirements can have large implications for the structure of banks' balance sheets and hence the real economy. Contrasting with this view, recent empirical evidence shows that there is vast heterogeneity in capital ratios, with many banks operating well-above the regulatory minimum (e.g., Flannery and Rangan 2008, Gropp and Heider 2010, Sorokina et al. 2017). This observation is consistent with papers arguing that the Modigliani and Miller (1958) capital structure irrelevance theorem can be extended to banks (e.g., Miller 1995, Admati et al. 2010, Kashyap et al. 2010, Admati and Hellwig 2013, Miles et al. 2013).

which is consistent with banks targeting a risk-weighted capital ratio (see, e.g., Berger et al. 2008, Flannery and Rangan 2008) and the Value-at-Risk rule of equity management sketched out in Adrian and Shin (2014). Finally, we observe a positive relation between changes in capital and liquidity ratios, illustrating that speci c adjustment actions such as reshu ing from loans to liquid assets help to improve both ratios simultaneously.

Using the estimated model, we simulate banks' decisions under the actual economic and institutional conditions during our sample period and then conduct a number of counterfactual simulations to investigate how banks adjust asset and liability structures in response to policy and economic shocks. The counterfactual simulations illustrate that changes in capital and liquidity requirements can have a material impact on banks' asset and liability structures and, consequently, aggregate lending in the economy.

The estimated model suggests that banks fully replenish their voluntary capital bu er in response to changes in the minimum capital requirements (but go no further), in line with recent empirical evidence provided by Bahaj and Malherbe (2017). At rst glance, this seems to justify the assumption of constant voluntary bu ers that is often taken in models studying the relation between bank capital and lending. However, our model illustrates that there is considerable heterogeneity in the way in which banks move to higher capital ratios, with important implications for the supply of loans. Adjustments are achieved by a combination of accumulating additional capital, reducing assets, and shifting from loans to liquid assets, where the overall magnitude and the relative strength of these e ects strongly depends on initial balance sheet conditions of the bank as well as the time elapsed since the policy change. Generally, banks that are initially more constrained (i.e., closer to the minimum capital requirement) choose socially less desirable adjustment strategies, reducing loans considerably more than banks that are initially less constrained. These results suggest that policy makers should account for initial balance sheet conditions in the banking sector when implementing policy changes, instead of assuming mechanical relations between capital regulation and lending. Moreover, our model suggests considerable di erences between transitory and medium- to long-term e ects of higher capital requirements. While banks tend to reduce loans in the short run, they also accumulate additional capital by retaining earnings, which allows them to support lending at higher levels than before in the medium to long-run. Thus, our paper dispels claims that higher capital requirements will lead to *permanent* reductions in lending and reconciles empirical evidence on a negative short-run impact of higher capital requirements and positive long-run e ects of higher capital ratios (e.g., Fraisse et al. 2015, Behn et al. 2016b, Jimenez et al. 2017 on the former, and Gambacorta and Shin 2016 on the latter).

We further show that also changes in liquidity requirements can have sizable real e ects, depending in particular on their interaction with capital requirements. Following an increase in liquidity requirements banks react by holding a larger amount of liquid assets. Ceteris paribus,

increasing the amount of assets decreases capital ratios, so that further adjustments are necessary if banks wish to maintain constant voluntary capital bu ers.[4] Our results show that these adjustments can involve a reduction in loans, in particular for banks that are initially more constrained by the liquidity requirement. Moreover, capital and liquidity ratios correlate positively in general terms, and both capital and liquidity structures tend to become more stable following changes in either requirement. However, banks generally compensate lower risk taking on the asset side by taking more risk on the liability side, e.g. reducing the average maturity of debt contracts. Consequently, under certain circumstances the decrease in solvency risk that is usually associated with an increase in capital requirements may be accompanied by an increase in liquidity risk, so that the aggregate impact on the riskiness of banks' balance sheets depends on the relative importance of solvency and liquidity risk. Overall, our results illustrate that there are complex interactions between capital and liquidity regulations, and that a comprehensive view on all dimensions is necessary in order to avoid potential unintended consequences of regulatory policies.

Our paper contributes to the literature by proposing a novel methodology to study the dynamic adjustment of bank capital and liquidity structures. While the literature on liquidity pro les is still scarce, previous papers studying the evolution of capital ratios have often used partial adjustment models, assuming the existence of target capital structures towards which banks adjust in case of deviations (see, e.g., Berger et al. 2008, Flannery and Rangan 2008, Gropp and Heider 2010, Memmel and Raupach 2010, De Jonghe and Öztekin 2015). While the concept is theoretically appealing, partial adjustment models are unable to distinguish between actual targeting behaviour and mean reversion due to purely mechanical reasons (see Shyam-Sunder and Myers 1999, Chen and Zhao 2007, Chang and Dasgupta 2009). The novel methodology used in our paper avoids this pitfall and is able to identify actual targeting behaviour.

In contrast to our model, theoretical papers on bank capital structure often focus on the socially optimal level of bank capital, i.e. the capital structure of the bank that maximizes its value for all stakeholders. Usually, the bank's optimal capital structure trades o some kind of bankruptcy cost against advantages of high leverage, due to agency problems (e.g., Diamond and Rajan 2000, Acharya et al. 2016), compensation for liquidity production (e.g., DeAngelo and Stulz 2015), tax bene ts (e.g., Gornall and Strebulaev 2015, Sundaresan and Wang 2016), the existence of deposit insurance (Allen et al. 2015), or simply the notion that equity is costly for banks for various reasons (e.g., Mehran and Thakor 2011). A number of papers also consider

[4] The result depends on the extent to which increasing the amount of liquid assets makes capital requirements more binding. In reality, this is more likely to be the case for banks that are relatively more constrained by the Leverage Ratio (i.e., an unweighted capital requirement). The reason for this is that liquid sovereign assets carry a risk weight of zero percent in many jurisdiction and hence do not require any equity nancing under the risk-based framework, while they do enter the denominator and can thus increase the bindingness of the Leverage Ratio.

the interaction between capital structure and asset risk (Shleifer and Vishny 1992, DeYoung and Roland 2001, Greenlaw et al. 2008, Adrian and Shin 2010, 2014). In contrast to many of these papers, we develop a positive dynamic model of bank adjustment behaviour, in which banks determine their asset and liability structures based on private considerations (with social implications).

The paper also relates to studies on the relationship between bank capital or liquidity and aggregate lending or real economic activity. One approach in this eld is to use micro-level data in order to identify how banks adjust lending behaviour in response to speci c policy changes or economic shocks (e.g., Peek and Rosengren 1997, Aiyar et al. 2014, Fraisse et al. 2015, Behn et al. 2016b, Jimenez et al. 2017). Another approach is to investigate historical correlations between uctuations in bank capital and other variables of interest (e.g., Bernanke et al. 1991, Hancock and Wilcox 1993, 1998, Berrospide and Edge 2010, Noss and To ano 2016, Gross et al. 2016). Virtually all of these studies rely on reduced form estimates of past behaviour, which may compromise their suitability for analysing the possible e ects of future policy changes (see Lucas 1976). The structural nature of our model seeks to overcome this challenge, as it establishes a microeconomic foundation for observed adjustments in capital and liquidity ratios and thus allows deriving economically founded behavioural responses to changes in capital or liquidity requirements.

Finally, our paper adds to a small but growing literature studying the interaction of multiple requirements in the post-crisis regulatory environment. Closely related is the paper by Mankart et al. (2018), who develop a dynamic structural banking model to examine the interaction between risk-weighted capital ratios and unweighted leverage requirements while abstracting from the liquidity dimension. The same applies to Goel et al. (2017), who take a capital allocation perspective and also study the interaction between risk-based capital requirements and a simple leverage ratio. The interaction between Basel III type capital and liquidity requirements is studied by Cecchetti and Kashyap (2016) and Chami et al. (2017). The former paper investigates potential redundancy of di erent types of requirements, while the latter develops a dynamic model for bank holding companies and studies how di erent types of investments on the asset side interact with each other. Finally, a number of papers seek to assess the macroeconomic e ects of multiple constraints on bank capital and liquidity (e.g., Covas and Driscoll 2014, Boissay and Collard 2016, Fender and Lewrick 2016). Our paper contributes to this literature by illustrating the trade-o s that banks need to consider in an environment with both capital and liquidity requirements in a dynamic setting, and by o ering insights on how capital and liquidity requirements may interact to determine the response of banks to changes in either capital or liquidity requirements.

The remainder of the paper is organized as follows: we develop our model in the next section and describe the data set and estimation strategy in Section 3. Results of the estimation are

presented in Section 4, and results of the counterfactual simulation are shown in Section 5. Finally, Section 6 concludes.

2 Model

We develop a dynamic stochastic model of bank behavior in the presence of economic uncertainty and regulatory constraints on capital and liquidity ratios. The model allows to study how banks take joint decisions with respect to asset growth, debt issuance, risk taking and payout policy, this way providing a microeconomic foundation for the observed bank capital structures and liquidity pro les and their dynamic adjustments. The following subsections include a description of the model setup, the timing of events and decisions, the exogenous processes of the model, the decision variables, the evolution of pro ts, the dynamics of capital and liquidity structures, and banks' dynamic optimization problem.

2.1 Model setup

The stylized bank balance sheet in our model is illustrated in Figure 1. It comprises two classes of assets, loans and liquid assets, and four classes of liabilities, deposits, long- and short-term debt, and equity. Decisions on how to adjust these asset and liability classes are taken by risk-neutral managers in a discrete time, in nite horizon setting. These managers maximize shareholder value in each period by jointly determining asset growth and structure, payout ratios (dividend distribution and recapitalisation) and the nancing mix between short-term and long-term debt, while considering various trade-o s simultaneously. Taking more risks allows them to generate higher expected returns, but comes at the risk of potentially larger shocks that may lead to a deterioration in capital and liquidity ratios. Banks face regulatory requirements on both of these ratios, and shareholders incur a cost in case the bank violates either type of requirement (or if the bank decides to raise external equity in order to avoid breaching the capital requirement). Our model features ex ante heterogeneity with respect to bank balance sheet size, asset composition and liability structure. Heterogeneity in later periods also depends on the realization of shocks on asset returns, cost of funding and volume of deposits.

2.2 The timing of events and decisions

The timing of events is illustrated in Figure 2. In each period, banks start with loans $L_{j,t}$, liquid assets $F_{j,t}$, equity $E_{j,t}$, deposits $D_{j,t}$, long-term debt $LT_{j,t}$ and short-term debt $ST_{j,t}$. Thereafter, banks take decisions on the payout policy $div_{j,t}$, the issuance of new loans $g^L_{j,t}$ and

new long-term debt $g^{LT}_{j,t}$, and the adjustment of liquid assets $g^{F}_{j,t}$ and short-term debt $g^{ST}_{j,t}$. They take these decisions to maximize:

$$\mathsf{E}_t\Bigg[\sum_{s=t}^{T}\beta^{s\ t}\Bigg(\underbrace{div_{j,t+s}}_{\text{future dividends}} - \underbrace{\times\ \mathbb{1}(CR_{j,t+s}<\theta_{CR})}_{\text{cost of breaching capital requirements}} \tag{1}$$

$$- \underbrace{\times\ \mathbb{1}(LR_{j,t+s}<\theta_{LR})}_{\text{cost of breaching liquidity requirements}} - \underbrace{_1(-div_{j,t+s})^{\ 2}\times\mathbb{1}(div_{j,t+s}<0)}_{\text{cost of raising fresh equity}}\Bigg)\Bigg]$$

with $\beta < 1$ being the discount factor and $\sum_{s=t}^{T}\beta^{s\ t}\ div_{j,t+s}$ representing the stream of expected future dividends. The remaining terms of the expression re ect the two types of frictions in our model. First, the variables and represent the costs of falling below regulatory capital (θ_{CR}) and liquidity requirements (θ_{LR}). These costs are reminiscent of the bankruptcy cost in classical trade-o theory models (see, for instance, Kraus and Litzenberger 1973 or Buser et al. 1981) and can be motivated by the risk for shareholders to be bailed in, possible restrictions on dividend payments, or other supervisory measures that may be imposed in case of a breach of requirements.[5] Second, when raising fresh equity in the market ($div_{j,t} < 0$) banks pay a cost equal to $\phi_1(-div_{j,t+s})^{\phi_2}$. These costs are meant to re ect the existence of direct transactional costs and indirect costs of raising equity, e.g. related to debt overhang problems (Myers 1977, Admati et al. 2012) or signaling costs (Myers and Majluf 1984). The assumption that raising new external funds is costly is common in the banking literature (e.g., Greenwald et al. 1993, Kashyap and Stein 1995, Froot and Stein 1998, Stein 1998, Valencia 2014) and consistent with the observation that banks are often reluctant to tap the market for fresh equity. In line with pecking order theory, the cost does not apply if banks decide to accumulate capital from retained earnings. Importantly, both the costs of breaching minimum capital and liquidity requirements and the cost of raising fresh equity are not imposed ex ante but estimated within our model structure. Hence, our model allows to test both trade-o and pecking order theories, since a zero value for either cost parameter would imply a rejection of the respective theory.

The structural parameters β, , , $_1$ and $_2$ are crucial elements in determining banks' adjustment functions and are estimated making use of the economic model (see Section 3.2). Given the structural parameters, the evolution of balance sheets depends on banks' decisions $_{\mathbf{j,t}} = (div_{j,t}, g^{L}_{j,t}, g^{F}_{j,t}, g^{LT}_{j,t}, g^{ST}_{j,t})$ and realized pro ts. Pro ts, in turn, depend on banks' decisions and the realization of shocks on asset returns, cost of funding, and the volume of deposits (see next subsection).

[5] Our model abstracts from potential agency problems between bank managers and shareholders. However, breaching requirements may also have personal consequences for managers who could be removed in such case.

Capital and liquidity regulation Finally, the institutional framework is characterised by the presence of minimum risk-weighted capital requirements θ_{CR} and liquidity requirements θ_{LR}. The regulatory requirements are such that $CR_{j,t+1} > \theta_{CR}$ and $LR_{j,t+1} > \theta_{LR}$ $\forall j$ = 1, ...J and t = 0, ...$T-1$. As speci ed in Eq. 1, banks face costs and/or when breaching these regulatory requirements. The introduction of costs associated with the violation of regulatory requirements, in a context with uncertainty and credible liability and asset structures, allows to investigate the role of regulation in the evolution of capital and liquidity pro les. In particular, we test whether and how much regulatory requirements are indeed important determinants of banks' capital and liquidity pro les by estimating the values of and : a rejection of the null hypothesis of (or) equal to zero would indicate that minimum requirements are indeed an important factor for banks' decisions on capital and liquidity pro les. In particular, the interplay between pro tability, the cost of equity, the level of uncertainty and the costs of breaching regulatory requirements shapes banks' decisions and induces optimal bu ers held on top of either minimum requirement in order to insure against possible shocks. Generally, these bu ers can be expected to be larger the larger costs of breaching capital and liquidity requirements. Moreover, positive parameter values for and would be consistent with classical trade-o theories of capital structure, since the cost of breaching regulatory requirements are reminiscent of the bankruptcy cost usually included in such models.

2.7 Banks dynamic programming problem and solution of the model

The evolution of the entire balance sheet structure can be pinned down by means of ve state variables, collected in the vector $_{\mathbf{j,t}}$ = $(CR_{j,t}, CR_{j,t}, E_{j,t}, LA_{j,t}, DL_{j,t})$. The state variables are the capital and liquidity ratios, the level of equity capital, the share of loans in total assets $LA_{j,t}$ = $L_{j,t}/A_{j,t}$, and the share of deposits in total debt $DL_{j,t}$ = $D_{j,t}/(D_{j,t}$ + $LT_{j,t}$ + $ST_{j,t})$. The solution of our model derives banks' optimal decisions $_{\mathbf{j,t}}$ for each point of the state space, so that we can disentangle the relevance of di erent modes of adjustment for di erent balance sheet conditions.

Besides the state of the system, optimal decisions at each point in time depend on the exogenous nancial factors determining the data generating process for the stochastic variables (r_t^{CB}, μ, ψ, ϕ, ξ, κ^{LT}, γ, κ^{ST} and) and the remaining structural parameters β, , , $_1$, $_2$ and ζ. In each period t, banks start with loans and liquid assets funded by equity, deposits, long-term and short-term debt from time $t-1$, and receive pro ts from banking activity as described in Eq. 13.

In this set up, the dynamic optimization problem can be written as:

$$V_{j,t}(\ _{\mathbf{j,t}}) = \max_{\mathbf{\Gamma_{j,t}}} \Big[div_{j,t} - \ \times \mathbb{1}(CR_{j,t+s} < \theta_{CR}) \tag{19}$$

$$- \quad \times \mathbb{1}(LR_{j,t+s} < \theta_{LR}) - \quad {}_1(-div_{j,t+s}) \; {}^2 \times \mathbb{1}(div_{j,t+s} < 0) + \beta \mathbb{E}_t V_{j,t+1}(\quad {}_{\mathbf{j,t+1}}) \Big]$$

subject to the constraints listed in Eqs. (2) to (18) and the de nition of the state variables.

The problem cannot be solved analytically. Instead, we derive optimal decisions at each point of the state space via backward induction, using a standard value function iteration approach. That is, we assume that banks will be liquidated in some future period T (we set T = 100), paying out the entire equity in that period without taking any other decisions. Given the value function obtained for period T, we can compute optimal decisions in previous periods. In particular, optimal decisions for each point of the state space in period $T-1$ are determined such that they maximize the value function of the bank. Going back in time, this procedure is repeated until the policy functions converge.[10]

To solve the model we need to discretize the state variables $_{\mathbf{j,t}}$ and and the choice variables $_{\mathbf{j,t}}$, which we do by using an exponential grid for capital and equally spaced grids for the remaining variables (see Appendix Table A.1 for the exact parametrization). To account for the stochastic nature of the model, we take expectations with respect to the shocks on asset returns, cost of funding, and deposit volumes when deriving optimal decisions at each point of the state space. The density functions for the shocks are approximated, following Tauchen (1986), using gaussian quadrature method when performing the numerical integrations. Finally, we use linear interpolations to evaluate next-period's value function for values of the state variables that do not lie on the exogenous prede ned grids.

3 Data and estimation strategy

We solve the the model numerically by making use of granular supervisory data on bank balance sheets and income statements. This section describes our data set and estimation strategy and reports results for some standard capital and liquidity structure regressions.

3.1 Data

The data we use to estimate the model includes information on 116 institutions supervised by the European Single Supervisory Mechanism (SSM), covering the quarters from 2014-Q1 to 2016-Q3 and containing very granular balance sheet and income statement information. Descriptive statistics for the data are presented in Table 1, and a description of all variables is available in

[10] That is, we solve the model backwards for 100 periods and check that the policy functions have converged, i.e. $||\mathbf{\Gamma_t(\Theta)} - \mathbf{\Gamma_{t-1}(\Theta)}|| = 0$.

Appendix Table A.2. Banks in our sample are rather large, with average assets of more than €200 billion, which is in line with their status as SSM signi cant institutions.[11] As expected, the risk-weighted capital ratio is on average considerably higher than the unweighted capital ratio, re ecting the average ratio of risk-weighted assets to assets of 45 percent. We report two di erent values for the liquidity ratio: the rst one is the actual Basel III Liquidity Coverage Ratio (LCR) as reported by the banks, while the second is a proxy variable that we calculate in order to match the de nition of the liquidity ratio in our model as speci ed in Eq. 18 (see below for details on the calculation). The distributional characteristics of the two ratios are close to each other, making us con dent that we have obtained a good proxy. The table further shows that pro tability of European banks is rather low throughout the sample period, with the average quarterly return on assets being only slightly above zero. Finally, it includes a breakdown of assets and liabilities by counterparty: Exposures to corporates and households each account for roughly a quarter of the average bank's assets, with the government sector being the third most important sector. On the liability side, households are by far the largest counterparty, although the fraction of instruments with no speci c counterparty (inter alia including debt securities issued, capital and subordinated liabilities, and derivatives) is sizable.

3.2 Estimation strategy

This subsection presents the strategy we use to estimate the structural parameters of the model. The parameters are estimated such that the model describes a number of key features of banks' behavior with respect to the level and the adjustment of their (risk-weighted) capital and liquidity structures. We use a two-step strategy similar to that employed, among others, in Gourinchas and Parker (2002). In the rst step, the parameters and functions characterising the exogenous stochastic processes in the model (r_t^{CB}, μ, ψ, ϕ, ξ, κ^{LT}, γ, κ^{ST}, and) are estimated directly from quarterly supervisory data. In the second step, we estimate the remaining structural parameters (β, $_1$, $_2$, , , and ζ) by targeting empirical moments characterizing the dynamic behavior of banks in our data, taking as given the values of the exogenous parameters estimated in the rst step.

Exogenous parameters The supervisory data contain detailed balance sheet information that allow us to estimate the parameters characterising the pro t function. These are key ingredients to our analysis and re ect on the nancial conditions which banks face over the sample period. The data include detailed information on the items that compose the statement

[11] According to the SSM Framework Regulation, all institutions with total assets larger than €30 billion are considered signi cant. Moreover, institutions are considered signi cant if their assets exceed 20 percent of national GDP, if they are one of the three largest credit institutions in a country, if they receive direct assistance from the European Stability Mechanism, or if they have signi cant cross-border activities.

of pro ts and losses, allowing us to back up the spread on loans μ and liquid assets ψ, the interest rate paid on deposits, short term debt and long-term debt, as well as administrative expenses and the fees and commissions margin (the aggregate of which constitutes the operating cost ι).

The estimated exogenous parameters, obtained as median values of the banks in our sample, are reported in Panel A of Table 2. The median value for the interest rate on the ECB's main re nancing operations within our sample period is 0 percent. As expected, loans generate higher returns than liquid assets (before considering the expected impairment rate ζ which we estimate below). To estimate the parameters κ^{LT} and κ^{ST}, we regress interest rates on short- and long-term debt on bank leverage and report the results in Table 3. The coe cient of interest is insigni cant and close to zero in all speci cations, indicating that there is no strong relation between interest rates on liabilities and banks' leverage during our sample period.[12] A possible explanation for this result is that our sample period coincides with extraordinary monetary policy measures in the euro area. The excess liquidity resulting from these measures could have compressed interest rate spreads for banks with more risky balance sheet structures, so that the relationship between a bank's riskiness and its cost of funding got blurred. Another possible reason is that a large portion of the lending between nancial intermediaries takes the form of collateralized transactions (such as repos), and the riskiness of the counterparty may be less relevant for pricing in such transactions. In any case, since there is no signi cant relationship in the data we simplify Eqs. 6 and 7 by setting κ^{LT} and κ^{ST} equal to zero and imposing homogeneous mark-ups ξ and γ across banks.[13] Panel A of Table 2 shows that both deposits and short-term debt are considerably cheaper than long-term debt. Moreover, the parameter ι_2 in the function for operating costs is smaller than one, illustrating that there are indeed some economies of scale in operating the bank. Finally, we assume that loans have an average maturity of ten years, re ecting the maturity of a standard mortgage contract, while long-term debt has an average maturity of eight years.

Shock variances Uncertainty plays a crucial role in our model regarding the accumulation of additional bu ers on top of minimum capital and liquidity requirements. We estimate the variances of the shocks to the return on loans, the return on liquid assets (and their prices), the cost of nancing and the volume of deposits directly from the data. We use a two-step empirical strategy to estimate the variances of these shocks.

In the rst step, the aim is to separate the endogenous variation in the measures of return, borrowing costs and deposits from the components that are exogenous to banks' behavior and can hence be interpreted as structural shocks. We construct the shocks $H_{j,t}$ by regressing the log

[12] Coe cients remain insigni cant when including quadratic terms.

[13] A negative relation between capital ratios and the cost of funding would facilitate adjustments and provide additional incentives to opt for higher capital ratios.

di erences of returns on loans, returns on liquid assets, pro ts from trading, interest expenses on short-term debt, interest rates on long-term debt, and deposits, respectively, onto observable characteristics. The set of characteristics include the lagged size of the bank (as the logarithm of total assets), and the (lagged) structure of assets (or liabilities, in the equations for $\eta_{j,t}^{iS}$ and $\eta_{j,t}^{iL}$) with respect to the types of instruments held (equity, debt securities, loans and derivatives) and counterparties (central bank, governments, banks, other nancial institutions, non- nancial corporations and households).

In the second step, we estimate the variances of the shocks using the second order moments for the log di erences of returns on loans, returns on liquid assets, pro ts from trading, interest expenses on short-term debt, interest rates on long-term debt, and deposits, and a GMM strategy, similar to that in Blundell et al. (2016), that allows to deal with the structural equations describing the evolution of rate of returns, costs of nancing, and deposits presented in Section 2.7. The standard deviations of the shocks derived as described above are reported in Table 2, Panel B. As expected, returns on loans are more volatile than returns on liquid assets. Moreover, the cost of long-term debt uctuates less than the cost of short-term debt. Finally, uctuations in deposits can be sizable, with a standard deviation of 3.1 percent.

Regulatory requirements In order to calculate risk-weighted capital ratios we need to obtain risk weights for loans and liquid assets, as well as risk charges for operational risk. We calibrate the model based on median values observed in the actual data, which are reported in Panel C of Table 2. Moreover, the liquidity ratio de ned in the Eq. 18 requires the speci cation of weights on short-term debt and deposits. In line with Basel Committee on Banking Supervision (2013), we require that the entire short-term debt and ve percent of deposits from households and non- nancial corporations need to be included in the denominator of the liquidity ratio (i.e., w^{ST} = 1 and w^{D} = 0.05).

Finally, we need to specify regulatory requirements on both capital and liquidity ratios. The capital requirement of 12 percent re ects average minimum Pillar 1, Pillar 2, and combined bu er requirements for the SSM signi cant institutions in our sample.[14] For the liquidity ratio, we need to translate requirements on the Basel III Liquidity Coverage Ratio (LCR) into requirements on our simple liquidity ratio as de ned above. We do this by comparing, for the banks in our sample, the level of our liquidity ratio (median of 1.22, see Table 1) with the level of the actual LCR as observed in the supervisory data (mean of 1.33). By dividing 1.22 by 1.33 we obtain

[14] The minimum Pillar 1 requirement is 8 percent, consisting of 4.5 percent common equity tier 1, 1.5 percent additional tier 1, and 2 percent tier 2 requirements. The average Pillar 2 requirement of SSM signi cant institutions is 2 percent, the capital conservation bu er requirement for 2016 is 1.5 percent, and additional bu ers for systemic institutions are on average 0.3 percent, summing to a total requirement of 11.8 percent, which we round to 12 percent (see European Central Bank 2016). Applicable rates for the Countercyclical Capital Bu er have been 0 percent in all SSM countries throughout our sample period.

a factor of approximately 0.9, which | if applied to the nal LCR requirement of 1.0 | yields a minimum requirement of 0.9 on our liquidity ratio.

Structural parameters estimation Given the exogenous parameters reported in Table 2, we use a Simulated Method of Moments approach to estimate the remaining structural parameters of the model, i.e. the discount factor β, the regulatory costs and related to the violation of capital and liquidity requirements, the parameters of the convex costs associated with raising fresh equity $_1$ and $_2$, and the expected impairment rate on loans ζ. We use the information in the supervisory data to pin down these additional parameters.

The estimation strategy comprises the following steps: rst, we solve the model as described in Section 2.7, given the set of exogenous parameters estimated from the data, for a given set of structural parameters. Second, we use the derived policy functions ( ) to simulate the dynamic behavior of 2000 banks over 200 periods. We use the simulated pro les for the decisions and state variables to generate a simulated panel data set that matches the composition of the observational data.[15] We target empirical moments that provide a comprehensive representation of both the balance sheet structure in the cross-section and of the dynamic evolution of the variables impacting capital and liquidity pro les. A complete list of the moments that we target, and the description on how they are computed, is reported in the Appendix, Table A.3.

Third, we repeat the rst two steps to choose a collection of structural parameters (β, , , $_1$, $_2$, ζ) that minimizes a weighted distance between the moments estimated using supervisory data and those estimated using simulated data generated by the structural model. Hence, the structural parameters are jointly pinned down by the observed patterns in the data. However, it is worth highlighting which sources of variation in the data are particularly important for the identi cation of the individual parameters. First, identi cation of the discount factor relies heavily on the observed levels of the dividend over equity ratio, total assets and equity. Intuitively, a higher (lower) degree of shareholders' impatience increases (decreases) the dividend payout for any given level of pro tability, this way reducing (increasing) capital and decreasing (increasing) the ability of banks to nance asset expansion. The costs of breaching the minimum capital and liquidity requirements are mainly identi ed by the extent of the observed voluntary bu ers that banks hold on top of the minimum requirements. Clearly, higher costs would induce, ceteris paribus, a higher incentive to increase the bu ers as an insurance against the risk of facing these costs. Moreover, the relation between asset and risk growth helps identifying the cost of breaching minimum capital requirements, with higher costs inducing a stronger risk-weighted capital structure targeting behavior and hence a stronger negative relation between asset and risk growth. The observed relation between asset and capital growth (and asset and liability

[15] To avoid that initial conditions matter, we restrict the simulated data to the periods from 150 onwards when comparing simulated and empircal moments.

growth), together with the level of capital and assets, help pinning down the costs of raising external equity. In particular, lower (higher) costs of raising fresh equity in the market will induce a higher (lower) covariance between capital and asset growth and increase (decrease) the level of capital and assets, for a given level of shareholders' impatience. Finally, the identi cation of the expected impairment rate on loans relies heavily on the observed median risk weight, with expectations of high future impairment rates inducing a reshu ing from loans to liquid assets and hence a reduction in the median risk weight.

3.3 Capital and liquidity structure regressions

Before moving to the estimation results we illustrate that our data is comparable to (though more granular than) data sets used in previous studies. To do this, we estimate standard capital and liquidity structure regressions of the following form:

$$CR_{jct} = \alpha_c + \alpha_t + \beta X_{jct} + \epsilon_{jct} \tag{20}$$

$$LR_{jct} = \alpha_c + \alpha_t + \beta X_{jct} + \epsilon_{jct} \tag{21}$$

The dependent variable is either the risk-weighted or the unweighted capital ratio or the liquidity ratio. Explanatory variables are summarized in the vector X_{jct} and include various balance sheet and income statement variables. Further, time and country xed e ects account for unobserved heterogeneity across countries and over time. Standard errors are clustered at the bank level to account for heteroscedasticity and serial correlation of error terms.

Estimation results for Eqs. 20 and 21 are presented in Table 4. In line with previous evidence (see, e.g., Berger et al. 2008, Flannery and Rangan 2008, Gropp and Heider 2010), we nd that size is negatively related to risk-weighted and unweighted capital ratios and liqudity ratios, while the relation with pro tability tends to be positive (Titman and Wessels 1988, Rajan and Zingales 1995, Frank and Goyal 2009 nd similar evidence for non- nancial corporations).[16] Not surprisingly, the amount of liquid assets is the most important determinant for our proxy of the liquidity ratio, while deposits exhibit a negative sign, which is expected given that they increase the denominator of the ratio. Interestingly, our results also illustrate that the riskiness of bank assets is a strong predictor of capital ratios. As expected, higher average risk weights (mechanically) decrease risk-weighted capital ratios as they in ate the amount of risk-weighted assets included in the denominator (see columns 1-2). However, there is a positive relation

[16] The negative coe cient on size may re ect both arguments according to which larger rms tend to be better diversi ed, reducing the probability of failure and allowing them to operate with lower capital and liquidity bu ers, and too-big-too-fail considerations by which large banks do not fully internalize the costs of bankruptcy and hence opt for lower bu ers. The positive coe cient on pro tability in the capital regressions is consistent with the pecking order theory, according to which rms will prefer internal funding over issuing debt (see Myers and Majluf 1984).

between average risk weights and unweighted capital ratios, suggesting that banks with more risky assets compensate this by maintaining higher unweighted capital ratios (see columns 3-4). This illustrates that asset and liability structures are likely to interact with each other and justi es our e orts to investigate the determinants of banks' joint decisions on these variables.

4 Results

This section provides results for the estimation of the model and illustrates how it succeeds in matching a number of key balance sheet characteristics and dynamic moments observed in the supervisory data.

4.1 Estimation results

Panel A of Table 5 shows estimation results for the structural parameters of our model. The estimated value of 0.986 for the quarterly discount factor is standard and corresponds to an annual cost of equity of roughly 6 percent.[17] The cost of breaching regulatory capital or liquidity requirements are 46 and 28 percent of total capital, respectively. Using these values, the model delivers median capital and liquidity ratios that get close to the ones observed in the data. This provides evidence that regulation plays a crucial role in determining the levels of observed capital and liquidity ratios and provides an explanation for the extent of bu er held on top of the minimum requirements: facing shocks to future pro tability or liquidity pro les, banks nd it optimal to insure themselves against the risk of breaching the regulatory requirement by keeping su ciently large voluntary bu ers (compare with Brunnermeier and Sannikov 2014 and Valencia 2014). The estimated cost of breaching liquidity requirements is considerably lower than the one for breaching capital requirements. This illustrates that liquidity requirements are perceived to be less binding than capital requirements, or | in other words | banks expect a less severe supervisory reaction when they breach liquidity requirements, compared with capital requirements. This feature is consistent with the rationale of the Liquidity Coverage Ratio, which is meant to be breached in times of nancial stress (see Basel Committee on Banking Supervision 2013).

The cost of raising equity can be interpreted as a fraction of the capital raised; the estimated parameters for $_1$ and $_2$ imply a convex relationship between the cost of raising fresh equity and the amount being raised. The magnitude of the parameters is such that raising equity is relatively costly, so that banks make use of this measure only in exceptional circumstances (in

[17] The quarterly discount factor (DF) of 0.986 corresponds to an annual DF of 0.945, which is converted into the cost of equity (COE) according to the following formula: $COE = \frac{1}{DF} - 1$.

the absence of policy changes, less than one percent of the banks in our sample raise fresh equity in each period). The expected impairment rate on loans equals 0.110 percent, which is very close to the realized impairment rate of 0.118 percent that we observe in the data. This suggests that banks base their expectations on future impairments on realized impairments in the past. Considering this impairment rate, loans still provide higher expected returns than liquid assets, since $\mu - \zeta > \psi$, as expected.

4.2 Evolution of balance sheets

Overall, using the estimated structural parameters the model succeeds well in matching the key balance sheet characteristics reported in Panel B of Table 5. Both capital and liquidity ratios are slightly lower than in the supervisory data, where a possible reason for this is the existence of additional supervisory guidance on top of requirements that may induce banks to hold larger voluntary bu ers than predicted by our model.[18] Moreover, the model does a good job in replicating the observed evolution of the dimensions that compose the banks' balance sheet and determine the adjustment of the risk-weighted capital structures and liquidity pro les (see β coe cients in Panel B). The co-movements between key variables a ecting capital and liquidity ratios in the actual and simulated data are also shown in Figure 3, where the sample is restricted to observations where the quarterly change in the respective variable is smaller than 20 percent. In this restricted sample that accounts for outliers the t between our model predictions and adjustments observed in the actual data is particularly good, as illustrated by the linear ts for the actual data (blue line) and the simulated data (red line) which overlap to a large extent.

Both the actual data and the predictions generated by our model con rm the ndings of Adrian and Shin (2014), with a strong co-movement between asset growth and liability growth. This illustrates that banks tend to leverage down (up) by selling assets to buy back debt (funding asset growth with new debt, see Panel A). Capital, on the other hand, is relatively `sticky': even though there is a slightly positive relationship between asset growth and changes in capital (suggesting that part of the asset growth is funded by retained earnings) the relationship in Panel B is much less obvious and atter than the one in Panel A. Interestingly, Panel C shows a negative relationship between changes in assets and changes in risk weights. This suggests that either an asset expansion is associated with reshu ing of the portfolio towards safer assets

[18] In the SSM area, so called Pillar II guidance is stacked on top of minimum requirements. While this bank-speci c $guidance$ does not constitute a requirement (in contrast to the Pillar II $requirement$), it re ects supervisory expectations with respect to an adequate level of capital and may be converted into a requirement if it is consistently breached by the bank. Hence, banks may be reluctant to operate with capital ratios lower than the guidance, treating it as a 'de facto' requirement and holding voluntary bu ers on top of it (see European Central Bank 2016 for further information on the stacking of requirements and guidance in the SSM area).

(associated with lower risk weights), or that an increase in risk weights is associated with an asset contraction, where both scenarios are consistent with banks targeting a risk-weighted capital ratio. Assuming that a higher Value-at-Risk (VaR) is associated with higher risk weights, such behaviour is also consistent with the VaR rule of equity management and the procyclicality of leverage documented by Adrian and Shin (2014). Panels D illustrates that there is no strong relation between changes in capital and changes in liabilities, while Panel E shows that the relation between changes in liabilities and changes in risk is similar to the one between changes in assets and changes in risk, which is not surprising given the strong correlation between movements in assets and liabilities. Finally, Panel F shows the positive correlation between changes in capital ratios and changes in liquidity ratios.

5 Assessing the impact of regulatory changes or economic shocks

Using the estimated model, we simulate banks' decisions under the actual economic and institutional conditions during our sample period and then conduct three counterfactual simulations to investigate how banks would adjust capital and liquidity structures in response to policy and economic shocks: (i) an increase in minimum capital requirement; (iii) an increase in minimum liquidity requirements; (iii) an increase in the expected impairment rate on loans.

5.1 Increase in capital requirements

Baseline effect The first policy experiment investigates the consequences of an increase in minimum capital requirements from 12 to 13 percent. Figure 4 reports the evolution of a number of key variables in response to the policy change. Risk-weighted capital ratios increase relatively fast and in proportion with the increase in requirements: one year after the change banks have adapted to their new target ratio, which is about one percentage point higher than before. There is little heterogeneity in the adjustment, with both the 25^{th} and 75^{th} percentile being close to the median adjustment. That is, most banks simply replenish the voluntary buffers they held prior to the change (but go no further), which is in line with recent microeconometric evidence provided by Bahaj and Malherbe (2017) for a granular panel data set covering 18 U.K. banks.

To validate the predictions of the model within our data set, we exploit heterogeneous increases in macroprudential capital buffer requirements faced by the systemically important financial institutions in our sample period. About half of the banks in our sample faced, in different periods, an increase in their capital buffer requirements. Exploiting these increases, we estimate a difference-in-difference regression model with multiple treatment periods, controlling for banks fixed effects as well as variables capturing banks' balance sheet structure. We run a similar

speci cation on the simulated data, comparing the behaviour of banks in the presence and in the absence of a one percent increase in minimum capital requirements.[19] The results are reported in Table 6 and indicate that the predictions of our model are in line with the e ects of additional bu er requirements estimated from the actual data. The 0.62 percentage point increase in risk-weighted capital ratios following a one percentage point increase in requirements compares with a 0.39 percentage point increase estimated from the data, and amply falls within its 95 percent con dence interval.

Mode of adjustment At rst glance, the results of this counterfactual experiment seem to justify the assumption of constant voluntary bu ers that is often used in studies on the relation between bank capital and lending or other economic outcomes. However, as we will show below, while the adjustment in the *level* of capital ratios is relatively homogeneous, there are substantial di erences in *how* banks adjust to the new target ratio, with important consequences for the evolution of loan supply.

Figure 4 shows that all of the adjustment modes discussed in Section 2.4 are re ected in banks' simulated responses. In the short-run, banks move to higher capital ratios by a combination of accumulating additional equity, reducing assets, and reducing asset risk by shifting from loans to liquid assets. For the median bank, equity increases by about 6 percent and remains at higher levels relative to the baseline scenario. The additional accumulation of equity is achieved by lower payout rates in the periods directly following the policy change (as we will show below, some banks also raise fresh equity). Loans are rst reduced by up to 0.5 percent for the median bank (and up to 1.9 percent at the 25^{th} percentile) and recover thereafter, for many banks exhibiting a slight increase relative to the baseline three years after the increase in requirements. The intuition for this development is that the additional equity accumulated in response to the policy change represents a relatively stable form of funding, and it is then attractive for banks to invest this stable form of funding into long-term assets which generally o er higher expected returns. Our ndings illustrate that the macroeconomic e ects of higher capital requirements depend on the time elapsed since the policy change and reconcile two di erent streams of the literature: on the one hand, the transition to higher capital ratios can be associated with reductions in loan supply, with potentially negative spillover e ects for the real economy (see, e.g., Aiyar et al. 2014, Behn et al. 2016b, and Jimenez et al. 2017 for recent evidence using micro-

[19] This analysis uses the baseline pro les, simulated by the model in the absence of the policy change, as control group. We restrict the simulated data to ve periods before and after the introduction of the policy change.

level loan data).[20] On the other hand, in the medium to long-term, better capitalized banks are better able to lend, so that the real effects of higher capital requirements can be positive (see also Gambacorta and Shin 2016).[21] Overall, the dominant channel for moving to higher capital ratios is to retain earnings, which is consistent with evidence presented by Cohen (2013) for the aftermath of the global financial crisis.

Heterogeneity in adjustment strategies Besides the observation that all banks tend to accumulate additional equity, the charts in Figure 4 show that there is considerable heterogeneity in banks' responses to the policy change. A main determinant of these heterogenous adjustments is the initial level of bank capitalization. To illustrate this, we allocate the 2000 banks in the simulated data into 50 equal-sized buckets, sorted by the level of the risk-weighted capital ratio at the time of the policy change (i.e., the 40 banks with the lowest capital ratio are in the first bucket, and so on). Figure 5 then shows the median policy-induced change in capital ratios, assets, loans, equity, dividends, and liquidity ratios in each of these 50 buckets. The first panel illustrates that the additional increase in capital ratios due to the policy change does not depend on initial capitalization: all banks increase their target capital ratio by about one percentage point relative to the baseline, except for very well capitalized banks that are less affected by the change. The qualifier *relative to the baseline* is important in this context, since banks that are close to the regulatory minimum aim to increase their capital ratios also in the absence of a policy change. This is illustrated in the first panel of Figure 6, which plots the total change in capital ratios following the increase in requirements for each of the 50 buckets (i.e., comprising both the change induced by the policy change and the change in the baseline scenario). As expected, banks that are closest to the minimum requirement increase capital ratios the most in absolute terms.

While the change in capital ratios relative to the baseline is homogeneous, there is considerable heterogeneity with respect to the adjustment of the underlying components. That is, banks' mode of adjustment in response to the change strongly depends on initial capitalization, with

[20] Compared with previous estimates in the literature, the short-run reduction in loans of 0.5 percent following a 100 basis point increase in capital requirements is at the lower end (e.g., recent empirical estimates by Bahaj and Malherbe 2017 show that the one-year change in loans following a 25 basis point increase in requirements varies between 0 and 0.7 percent, depending on economic conditions). A possible reason for this is that our model abstracts from negative signalling effects that may be associated with cutting back distributions. In the previous financial crisis, many banks kept paying dividends even when facing significant losses, since they were concerned that cutting back distributions could be perceived as a negative signal that would be punished by investors. Consequently, they preferred other modes of adjustments over cutting back distributions, including deleveraging. Introducing such dividend smoothing motives would likely increase the initial lending response in our model.

[21] Note that 'real effects' in this context refers only to the direct effects of higher capital requirement on lending. A fully-fledged cost-benefit analysis of changes in capital requirements would have to account also for higher resilience and reduced crisis probabilities that are likely to be associated with higher capital ratios (see, e.g., Behn et al. 2016a). Such an analysis is out of scope for this paper.

more constrained banks generally using less preferable adjustment strategies. Generally speaking, three di erent groups of banks can be distinguished. First, the group of banks with initially high capital ratios is only mildly a ected by the policy change. Target ratios for these banks increase, but the pressure to adjust quickly is limited since the banks have su cient bu ers on top of minimum requirements. Consequently, these banks move to higher capital ratios by cutting back dividends and retaining additional earnings, which allows them to maintain pro table lending business and does not induce the cost associated with raising external equity (see Figure 5, buckets 35 to 48). Second, banks that are closer to the minimum pay fewer (or no) dividends already in the baseline scenario, since they are operating below their target capital ratios and need to retain earnings in any case. Consequently, these banks can accumulate less additional capital by cutting back dividends. Moreover, they operate closer to the regulatory minimum and hence face higher pressure to improve capital ratios quickly. Consequently, in addition to cutting back dividends these banks reduce the amount of loans, since loans have a relatively high risk weight so that a reduction in their volume is e ective in increasing risk-weighted capital ratios. The chart illustrates that the lower the ability to retain additional earnings by reducing the amount of payouts, the higher the need for banks to reduce loans in order to decrease the denominator of the capital ratio (see Figure 5, buckets 8 to 35). Finally, the banks on the very left face the highest pressure to increase capital ratios quickly, since they are closest to the regulatory minimum. These banks cannot retain additional earnings, since they already retain all their earnings in the baseline scenario. Moreover, the amount by which they would have to cut back lending to achieve their target capital ratios is so large that it becomes preferable to raise external equity instead, despite the cost that is associated with doing so. The fresh equity allows them to maintain lending to a certain extent, so that the reduction in loans is less pronounced than for slightly better capitalized banks that do not raise fresh equity (see Figure 5, buckets 1 to 8).[22]

Impact on liquidity pro le Figures 4 and 5 also show that the changes in (risk-weighted) capital structure a ect the bank's liquidity position. Initially, the liquidity ratio strongly increases as banks reshu e from loans to liquid assets. This e ect gradually vanishes as adjustments on the asset side reverse. Moreover, reducing assets and accumulating additional equity allows banks to reduce the amount of debt, in particular long-term debt which is now replaced with another form of stable funding. The stronger reduction of long-term debt implies a shortening of the average debt maturity. Overall, three years after the policy change the liquidity ratio for the median bank is still higher than before, in line with the positive relationship between capital and liquidity ratios predicted by our model and observed in the data. However, a

[22] Banks that choose to reduce loans in response to the policy change $partly$ replace the foregone lending by investing in liquid assets. As a result, aggregate deleveraging is strongest for those banks, while at the same time liquidity ratios improve the most (see bottom of Figure 5).

number of banks compensate lower risk-taking on the solvency dimension by take more risk on the liquidity dimension, so that the liquidity ratio declines relative to the baseline. Depending on the relative importance of solvency and liquidity risk, this means that the overall balance sheet structure may become more risky for certain types of banks following an increase in capital requirements. However, the decline in liquidity ratios is relatively modest, and in general both asset and liability structure tend to become more stable in response to the policy change. This overall lower risk-taking also re ects into somewhat lower pro tability.

Discussion Overall, results in this subsection show that the macroeconomic e ects of changes in capital requirements are likely to depend on banks' initial balance sheet conditions. There are considerable di erences between transitory and medium- to long-run e ects, with the latter likely to be more positive than the former. Moreover, the illustrated non-linearities in the adjustment functions are important factors to be taken into account when assessing the short-term impact of proposed policy measures. Adjustment strategies involving a reduction in loan supply are arguably least desirable from a social perspective. Interestingly, such undesirable strategies are mostly chosen by banks that are close { but not too close { to the regulatory minimum prior to the policy change. An interpretation of this result is that a bank's lending reaction likely depends on the extent to which it is willing or forced to recapitalize by raising fresh equity in the market. To prevent undesirable adjustments also in the short-run, a possible option for supervisors could be to provide additional guidance to banks on *how* they should move to higher capital ratios, to make it more preferable for a larger portion of banks to raise external equity rather than cutting back loans.

5.2 Increase in liquidity requirements

Baseline e ect The second policy experiment analyses how banks' adjust their asset and liability structures in response to an increase in the liquidity requirement from 0.9 to 1.0. Results are reported in Figure 7. As in the previous policy experiment, banks adapt relatively quickly: one year after the policy change the median bank has reached its new target liquidity ratio, which is nine percentage points higher than in the baseline scenario. The change is slightly smaller than proportional, which can be explained by the lower cost that is associated with breaching the liquidity requirement and by the greater ex ante variation in liquidity ratios compared with capital ratios. As we will show below, a number of banks with initially high liquidity ratios are not at all a ected by the change in requirements, since they already have su ciently large voluntary bu ers on top of minimum requirements (see also the development 25^{th} percentile at the bottom of the chart).

Mode of adjustment and interaction with capital structure Adjustments occur on both the asset and the liability side, i.e. banks make use of both modes of adjustment discussed in Section 2.4. First, to improve the denominator of the liquidity ratio, many banks tend to replace short-term debt with long-term debt, so that the average maturity of their debt contracts increases and overall debt structure becomes more stable. Second, to improve the numerator of the liquidity ratio, banks tend to increase their holdings of liquid assets. In the absence of further adjustments, such an increase in liquid assets would imply a decrease in the risk-weighted capital ratio, as liquid assets enter the denominator with a positive weight. Since the target capital ratio is not a ected by the change in liquidity requirements, banks need to take further adjustments in order to keep the capital ratio relatively constant. The preferred option for many banks is to reduce loans, so that the total amount of assets remains constant while average risk weights decrease. The shift from loans to liquid assets and from short-term debt to long-term debt reduce the bank's pro tability, so that the ability to retain earnings is constrained and equity declines relative to the baseline scenario. Moreover, the larger share of less pro table assets also makes it less attractive for banks to use relative stable and expensive equity nancing, so that payouts tend to increase. As a result of the reduction in equity nancing the return on equity rebounds to a certain extent, following the initial decline in response to the policy change.

The reduction in loan supply in this second counterfactual is more pronounced and also more persistent than the reduction in the rst counterfactual. The intuition for this is as follows: in response to the change capital requirements banks accumulate additional equity, and as explained in the previous subsection it is attractive for them to invest this equity into long-term asset that generate relatively high returns, so that loans rebound and the initial reduction is mitigated. In contrast, following the change in liquidity requirements banks need to increase liquid assets. Their preferred form of funding for liquid assets is short-term debt, while using equity is not attractive from an investment point of view. As banks are unwilling to fund the expansion in liquid assets with additional equity, they need to take other compensatory measures in order to prevent a decline in capital ratios, so that they are forced to reduce loans. The reshu ing from loans to liquid assets decreases average asset pro tability and thus hampers also the ability to retain additional earnings, which contributes to a decline in equity and further reduces the bank's ability to extend new loans (since less equity is available to fund the loan growth).

Of course, the channel described above depends on our model feature that increases in liquid assets can amplify constraints on the capital dimension (i.e., that liquid assets have positive risk weights). In reality, banks can arguably increase their liquid asset holdings without decreasing the risk-weighted capital ratio, since domestic sovereign assets carry a risk weight of zero percent in many jurisdictions. In this case, the above channel would be mitigated and the resulting reduction in loan supply could be less pronounced. However, in reality banks

face requirements also on unweighted capital ratios (from which we abstract in our model for simplicity reasons), and sovereign assets *do* enter the denominator of the unweighted capital ratio in their full amount. Hence, a way to interpret our findings is that the real effects of changes in liquidity requirements are likely to be more pronounced the more banks' are constrained by the unweighted rather than the risk-weighted capital requirement, and the lower the supply of liquid assets with very low or even zero risk weights.

Heterogeneity in adjustment strategies As for the case of capital requirements, adjustments in response to the change in liquidity requirements are heterogeneous and depend on initial balance sheet conditions. Figure 8 shows that one year after the policy change banks that are initially closer to the minimum requirement exhibit a more pronounced increase in liquidity ratios relative to the baseline scenario, while a number of banks with initially very high liquidity ratios are not at all affected by the change in requirements. This pattern is driven by a stronger increase of liquid asset holdings for initially more constrained banks. In addition, the most constrained banks also reduce short-term debt, to improve the liquidity ratio quickly. They compensate the reduction in short-term debt by retaining additional earnings, so that capital initially increases and the capital ratio improves in lockstep with the liquidity ratio.[23] As described above, this development is reversed over the medium-term, as the lower share of loans reduce bank's ability and willingness to accumulate equity relative to the baseline scenario. In contrast, banks that are initially less constrained by the liquidity requirement prefer to adjust mainly on the asset side, financing the expansion in liquid assets partly with short-term debt and partly with long-term debt, so that the liquidity ratio improves less than for initially more constrained banks.

Discussion Overall, the results in this subsection show that also changes in liquidity requirements can have sizable real effects, under the condition that additional holdings of liquid assets make capital requirements more binding. As for changes in capital requirements, banks' mode of adjustment is highly non-linear and depends on their initial balance sheet structure. Perhaps somewhat surprisingly, long-run effects on loan supply are more pronounced than for capital requirements, which also reflects the observation that banks have fewer options to react to changes in liquidity requirements (see Section 2.6). While this result is partly driven by our assumption of positive risk weights for liquid assets, the real effects of changes in liquidity requirements are certainly an area that deserves to be studied further in the future.

[23] The improvement in capital ratios for this group of banks is due to both an increase in equity financing and a reduction in loans. It would have been less pronounced (about half the current magnitude) if the banks had used long-term debt rather than equity to compensate the reduction in short-term debt.

5.3 Increase in loan impairment rate

Besides regulatory requirements we can also study how banks adjust in response to changes in economic conditions. We simulate an economic downturn by implementing a 10 percent increase in the expected impairment rate on loans. Banks' adjustment functions are plotted in Figure 9. The increase in expected impairments reduces pro tability and thus banks' ability to accumulate earnings, so that the bank's equity declines relative to the baseline scenario. The lower amount of equity can nance only a lower amount of assets, so that in particular loans are reduced (since they are costly in terms of required equity nancing and less pro table than before). A number of banks compensate the reduction in loans by increasing liquid assets, so that liquidity ratios tend to increase, although the reshu ing on the asset side re ects into an increase in the relative importance of short-term debt. Finally, target capital ratios are virtually una ected by the change in economic conditions. The latter is mainly due to the way in which we proxy the economic downturn, i.e. as a *certain* decrease in expected pro tability. One may argue that a recession also implies greater uncertainty, associated with greater variability in expected returns. In this case, banks would react by keeping larger precautionary bu ers on top of regulatory requirements.

6 Conclusion

Our paper develops a structural model of bank behaviour that provides a microeconomic foundation for the observed uctuations in bank asset and liability structures and for the response to changes in regulatory capital and liquidity requirements or economic shocks. When deciding on asset and liability structures, bank managers trade o the ability of generating higher expected returns on equity (e.g. associated with higher leverage) against higher risks of breaching regulatory requirements or having to raise fresh equity. The estimated parameters of the structural model suggest that banks hold voluntary capital and liquidity bu ers for precautionary motives, to insure against solvency and liquidity shocks that could push ratios below or close to regulatory requirements.

The model suggests that banks' preferred mode of adjusting to higher capital requirements is to retain earnings, in line with evidence from the recent nancial crisis (see Cohen 2013). Moreover, while banks tend to reduce loans in the short run, the additional accumulated earnings allow them to support lending at higher levels than before in the medium to long-run. This is an important nding of our model, as it reconciles empirical evidence on a negative short-run impact of higher capital requirements on lending, and positive long-run e ects of higher capital ratios on loan supply.

We further show that also changes in liquidity requirements can have sizable real e ects, depending in particular on their interaction with capital requirements. Following an increase in liquidity requirements banks react by holding a larger amount of liquid assets. Ceteris paribus, increasing the amount of assets decreases capital ratios, so that further adjustments in the supply of loans are necessary if banks wish to maintain constant voluntary capital bu ers. Our results show that these adjustments can involve a *permanent* reduction in lending, in particular for banks that are initially more constrained by the liquidity ratio. This nding points to potential unintended e ects arising from the interaction of multiple regulatory constraints which deserve to be studied further.

A clear lesson from the model is that supervisors need to have a good understanding of initial balance sheet conditions when deciding about the calibration of possible policy measures. The overall impact of the measures, and in particular the short-term lending reaction (which is often used as a proxy for the potential cost of policy measures) is likely to depend on how binding the constraints are prior to the policy change. This points to the importance of tailoring regulatory measures to individual nancial institutions that may be characterised by di erent balance sheet structures. Future research should focus on investigating the importance of additional sources of heterogeneity among banks that may a ect the response to policy changes.

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Charts and tables

Figure 1:
Balance sheet structure.

The stylized bank balance sheet structure of our model comprises loans and liquid assets on the asset side, and capital, deposits, long-term debt and short-term debt on the liability side. Loans generate returns as speci ed in Eq. 2 and evolve according to Eq. 8. Liquid assets generate returns as speci ed in Eq. 3 and are subject to price movements (Eq. 4). They evolve according to Eq. 9. The evolution of capital depends on pro ts and payouts (Eq. 15), while we assume exogenously determined deposits subject to random shocks (Eq. 12); interest rates on deposits are de ned in Eq. 5. Finally, long-term debt and short-term debt evolve according to Eqs. 10 and 11, where banks have to pay interest rates as speci ed in Eqs. 6 and 7.

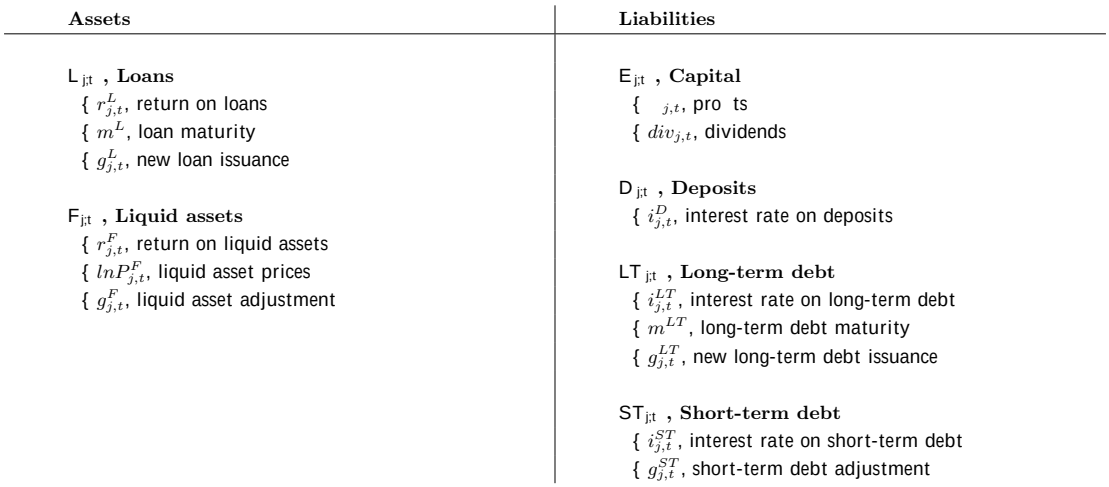


Figure 7:
Increase in minimum liquidity requirements.

The gure shows simulated counterfactual developments of key variables in response to a ten percent increase in minimum liquidity requirements, relative to developments of these variables without any change in liquidity requirements. The charts for capital ratios, liquidity ratios, risk weights, and dividends over assets show percentage point di erences between the counterfactual and the baseline simulation. The remaining charts show di erences in the logarithm of the respective variable between the counterfactual and the baseline simulation; the numbers in these charts can be interpreted as percentage deviations.

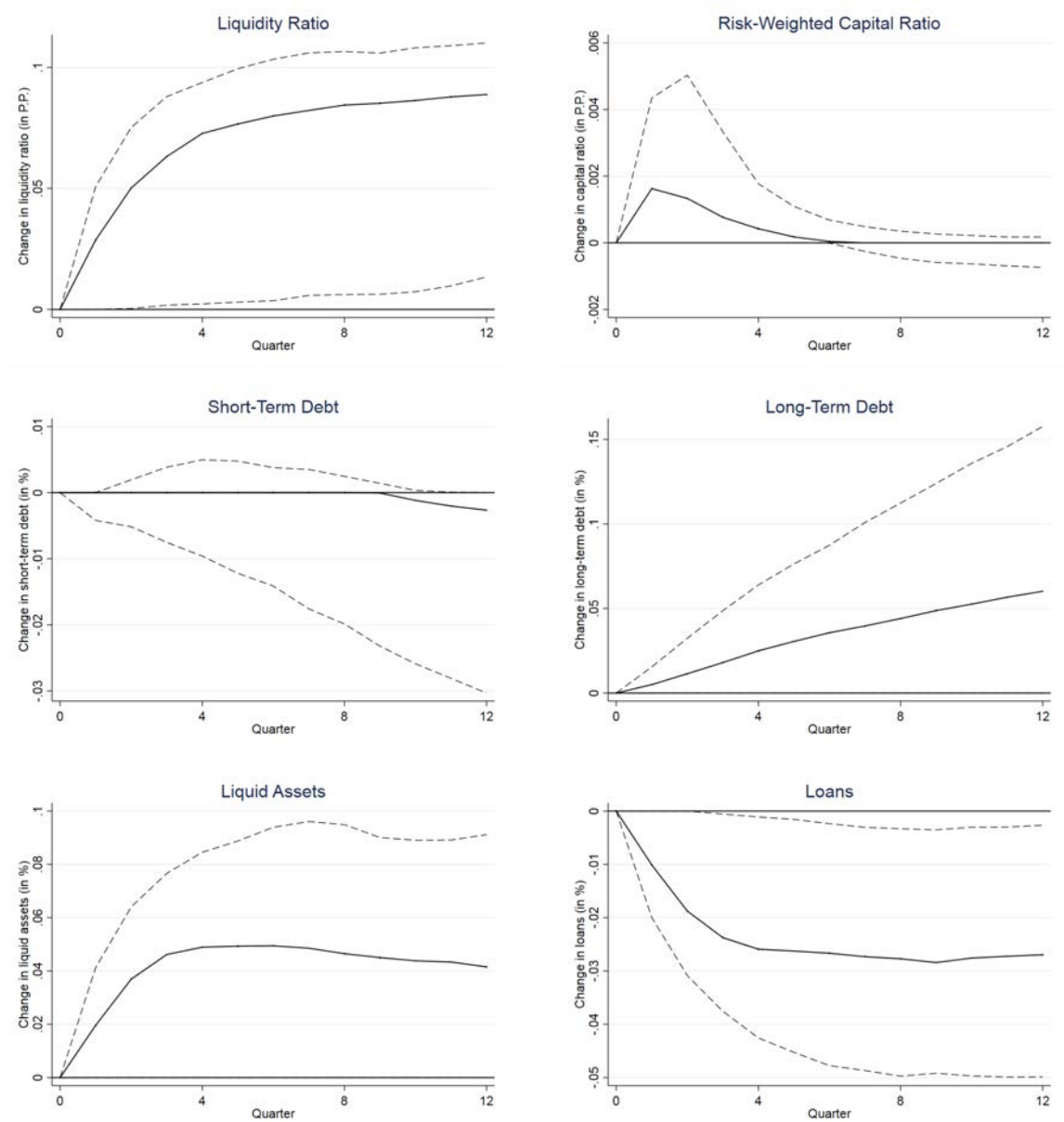


Figure 7 continued...

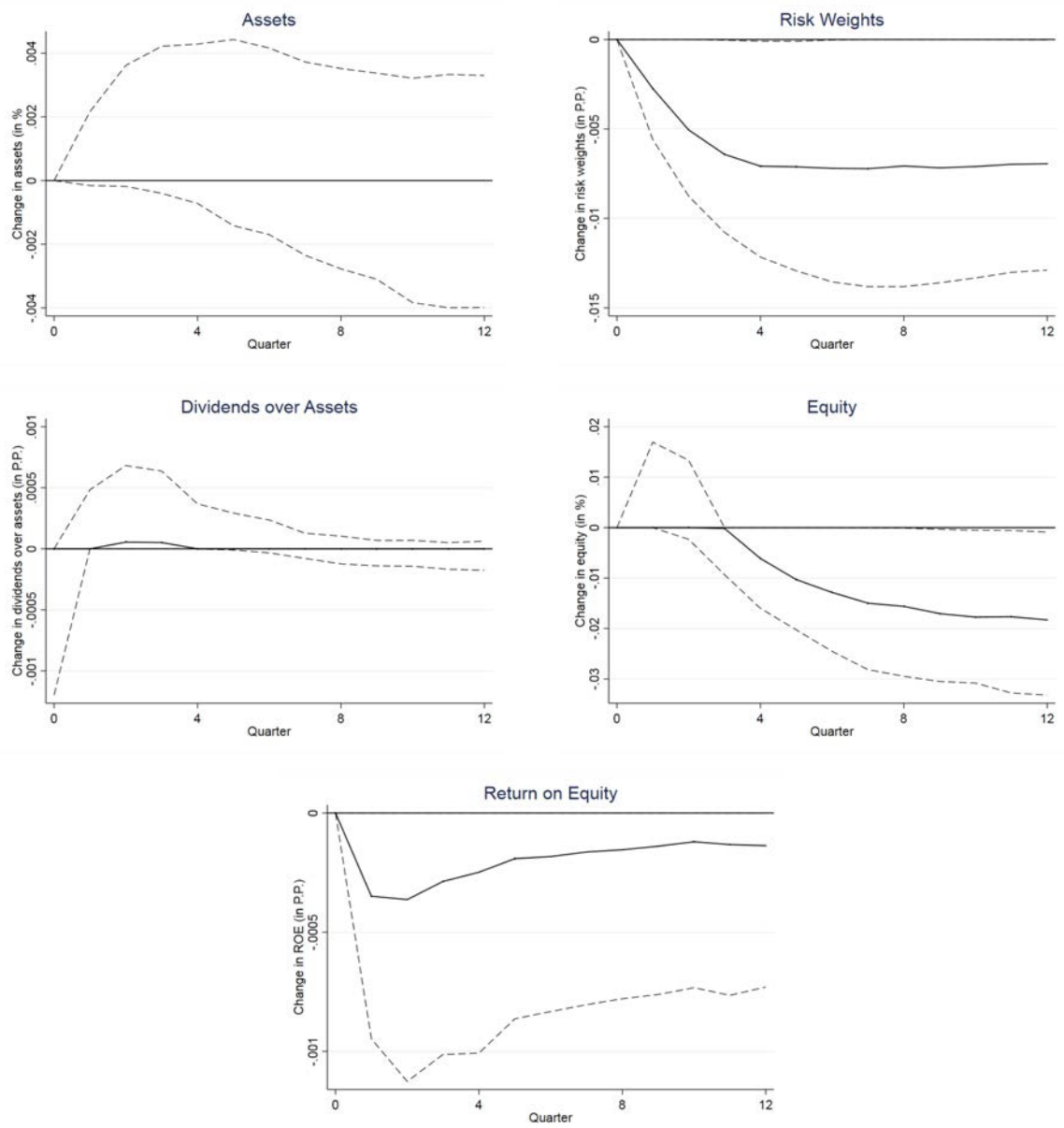
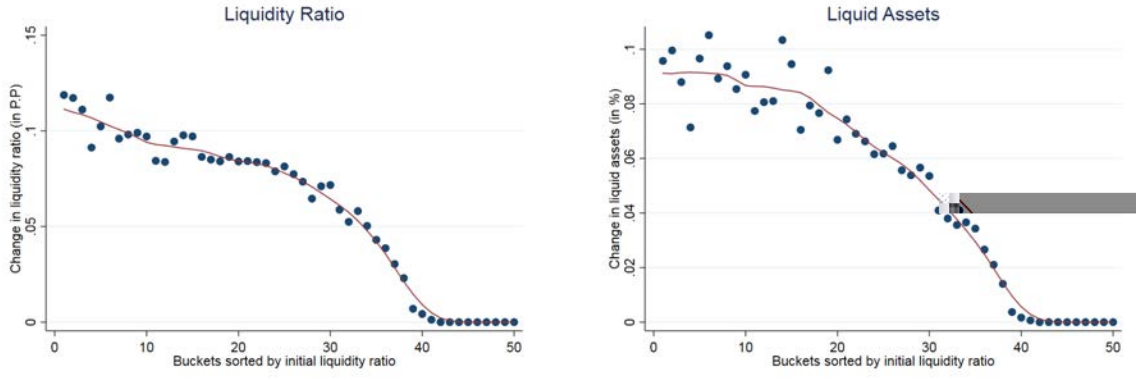


Figure 8:
Heterogenous response to change in liquidity requirements.

The figure shows the one-year change of key variables in response to a ten percent increase in minimum liquidity requirements, relative to developments of these variables without any change in liquidity requirements. Banks are sorted into 50 buckets, according to the value of their liquidity ratio at the time of the policy change (banks with the lowest liquidity ratio are placed in the first bucket). Each dot corresponds to the median change of the variable in the respective bucket. The red line is a local polynomial smooth, using an Epanechnikov kernel function with bandwidth of 2.5. The charts for capital and liquidity ratios show percentage point differences between the counterfactual and the baseline simulation. The remaining charts show differences in the logarithm of the respective variable between the counterfactual and the baseline simulation; the numbers in these charts can be interpreted as percentage deviations.